Innovative Design Concepts for Ultralightweight Space Telescopes

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Abstract

This paper represents the latest installment of "a work in progress" that began about seven years ago at NASA MSFC with the turbulence-correcting segmented optics for the Selene power beaming program, transitioned three years later to larger segments with an emphasis on low mass for the ULTIMA space telescope program, and continues today primarily through several SBIR efforts. This paper concentrates instead on the early stages of a Phase I SBIR that is currently being pursued by the author to develop concepts for lightweight mirrors and tensile-based structures for space telescopes with areal densities on the order of 1 kg/m^2..

1. Introduction

Although membrane mirrors or the like will eventually allow NASA to reach its ambitious long-term goal of 0.1 kg/m^2 for large space optics, there are a variety of reasons why it will be difficult to achieve, not the least of which is the fact that telescope primary mirrors like to be concave whereas membranes -- unless pressurized -- prefer to be flat. Techniques are being explored to actively control the local figure of membranes, but a flat approximates a curved surface only over very small regions, so the operators will probably have to be highly localized. This can be shown quite easily by noting that the RMS deviation of a sphere of radius R from a flat is $d^2/(16R\sqrt{3})$ over a disk of diameter d, so, for example, a flat region can be no larger than 1.7 cm to fit a curvature radius of even 100 meters to within 0.1µ.

It is natural then to consider the possibility of stiffening the "membrane" over larger regions to reduce the control requirements by mechanically producing the desired figure, but that in turn leads quite naturally to the concept of segmented optics. Such a mirror system is likely to be heavier than a membrane, but it should be able to bridge the rather large gap between the NASA goals and the 10+ kg/m^2 areal densities being achieved today with the NGST, and experience has shown that more highly-segmented optics, when properly configured in an overall system, can offer considerable benefits:

- Arbitrarily large mirrors can be produced with a reasonable number of conveniently-sized segments (e.g., about 400 one-meter elements for a 20 meter aperture)
- Spherical panels can be readily mass-produced to high optical tolerances by replication, and proper structural design can result in very low mass and minimal bending
- Spherical aberration can be corrected with the secondary mirror, and the primary can be mapped onto a segmented tertiary or quaternary for overall wavefront correction
- Rigid panels display only 3 DOF each, and image plane algorithms are available for unambiguous correction
- Edge diffraction is well understood, and need not be an issue.

These features and the earlier work have been discussed in detail elsewhere [(1) - (3)], and, aside from a brief discussion of an interesting candidate system, this paper concentrates on recent thoughts and developments in support structures and mirrors.

2. System Configuration

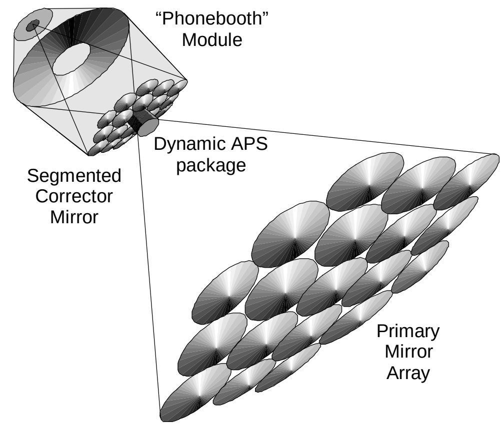

Fig. 1 ULTIMA configuration

The ULTIMA studies have shown that an especially attractive configuration for a very large space telescope is the three-mirror Gregorian design [(1)] shown schematically in Fig. 1. It uses a segmented spherical primary mirror whose aberrations are corrected by the appropriately-figured secondary mirror and whose deflections are corrected by the matched segmented tertiary mirror upon which the primary can be imaged and mapped one-to-one. Correction with the tertiary rather than with the primary itself makes the adaptive components far more accessible and considerably eases the problem of cooling the large primary mirror for operation in the infrared. The smaller optical components and the principal instrumentation are all located in a single relatively-small dimensionally-stable module that would provide highly-effective light baffling and that, perhaps, would facilitate servicing by allowing it alone to be returned to the Space Station (the unit was initially referred to as a "phonebooth" because of the size of the ISSA's service chamber, but the module quickly outgrew that name as the size of the telescope increased.) The internal focus at or near the tertiary mirror plays a very important systems role because it provides an ideal situation for mounting multi-function optics such as the dynamic alignment/pointing/ scanning (APS) package of Fig. 2.

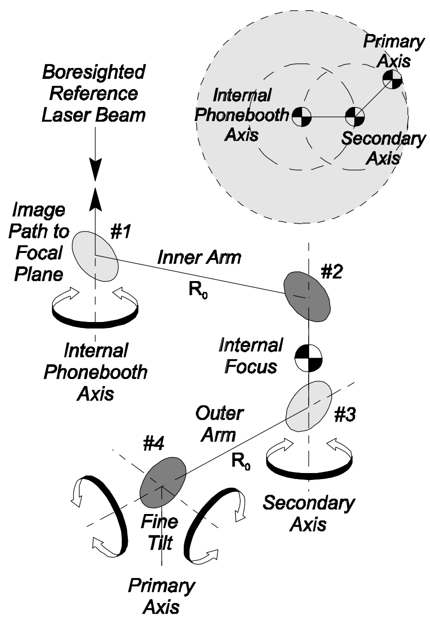

Fig. 2 Dynamic APS package

Field-of-view is a precious commodity with telescopes, and the APS can provide very large *dynamic* pointing capability on the order of degrees without large-body motion by sweeping the optical axis across the spherical primary with the "scanning" (#1) and "steering" (#4) mirrors. The others are required to prevent both an on-axis "blind spot" and image rotation, and axial spacing can be maintained by out-of-plane translation of any of the mirrors. Telescopes with both large field of view and high resolution would normally require a prodigious number of sensing elements, but, by providing large dynamic pointing with a moderate instantaneous FOV, the APS can easily maintain a fixed centroid position on a limited region of the instrumentation focal surface, and the image can furthermore be scanned across the surface for multispectral and other measurements. The ability of the APS to accommodate both steering and mirror separation changes may even permit the large primary mirror to be physically separate from the rest of the system, perhaps either free-flying or tethered with external metrology with lasers and small propulsion units used to maintain coarse alignment with millimeter-scale accuracy as in the functionally-rigid "spoked wheel" configuration proposed by JPL for its Multiple Spacecraft Interferometer Constellation (MUSIC) depicted in Fig. 3. *It is recognized that a performance compromise is being made here between the dynamic and instantaneous FOVs, but that is all part of good system tradeoffs.*

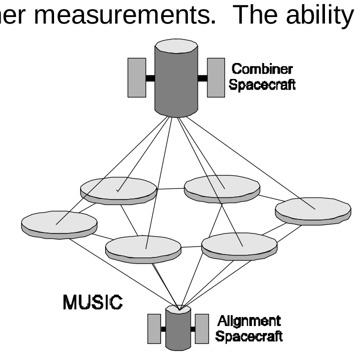

Fig. 3 JPL MUSIC spacecraft

A complete generalized paraxial ray optical analysis for such a three-mirror system with a spherical primary mirror was presented in Ref. 1.

3. Tension-Based Support Structures

The lightweight replicated mirror panels being developed by MSFC and, ultimately, the membrane mirrors under study by JPL may prove to be very attractive for large telescopes, but their value will by fully realized only if they are mated with equally low-mass support structures. "Conventional" designs with a multitude of stiff members and strong moment-bearing joints tend to much heavier than the more advanced mirrors, and far more promising, instead, is a tension-based truss structure, much like a sailboat mast with its spreaders and stays, that can be very stiff without incurring the mass penalties. Active control would, of course, be needed to control deflections, but tension adjustments in the cables might be used to correct the truss's own structural deformations, and individual actuators could be used for final adjustment of the mirror surface.

The author became interested in the subject of tension-based structures over forty years ago while a sophomore in Architecture at MIT. After he had experienced a less than auspicious start in a course in "Form and Design", the class was assigned a major project to individually design structures that would be erected and would stand primarily due to tension in the elements. Dangerously nearing the deadline for completion of the project, the fledgling designer suddenly envisioned his solution to the problem and set about building a model from a tangle of brass rods, steel wire, and model-yacht tumbuckles. The professor and the other students scoffed at the effort until, as the turnbuckles were tightened, a handsome domed structure began to rise into the air, and all but the author were astonished when it was found to be surprisingly strong. The model was transferred to the Architecture Museum there, the author transferred back into Engineering, and all was well until several years later when, thinking to pursue the patent suggested by the professor, he attempted to "improve" the aging model, and the structure fatally collapsed when the wires snapped after being excessively stretched.

That design, shown in Fig. 4, used an outer array of short vertical posts arranged in a ring and anchored in the base. Another "floating" ring of vertical posts were suspended radially from them by tension elements and from one another by circumferential wires, and the process was repeated towards the center as many times as necessary to produce the desired shape.

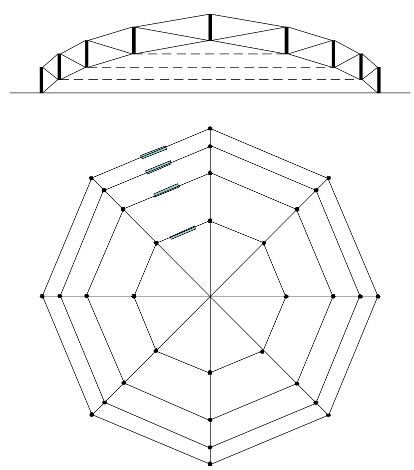

Fig. 4 1957 student project design

It, of course, was a ground-based structure whose radial support was provided by the moments imposed on the outer posts by the ground, but it may be possible to extend the design to a large deployable space telescope structure by providing radial compression members as shown in Fig. 5. None of the joints have to support moments, so they can be of simple low-mass pin design, and it should further be possible to lightly spring load them to permit automatic deployment. The pinned joints also mean that the longer compression members need to be designed only for buckling, not for bending, and this should significantly reduce their mass as well.

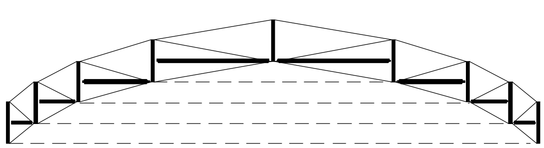

Fig. 5 Free-standing configuration with radial struts

A better answer for NASA may lie, however, in the structures pioneered by the sculptor Kenneth Snelson whose soaring masterpiece “Needle Tower” (Fig. 6) dominates the Hirshhorn Museum and Sculpture Garden in Washington D.C. He called his design concept "floating compression", but it is better known today by the term "tensegrity" which was coined by his teacher, the architect/ mathematician R. Buckminster Fuller. The term refers to the structures' integrity under tension, and the concept is being widely-publicized today through articles in popular scientific journals [4] [5] and through a myriad of dedicated Web sites.

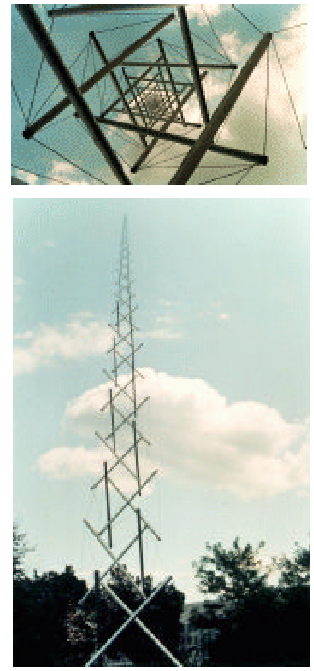

Fig. 6 Needle Tower

Notwithstanding their artistic merit, the structures are of particular interest for large space-based mirror support because of the extremely low mass afforded by the absence of bending moments in the compression members and by the potential ease of storage and deployment of the flexible tension elements and the short compression ones. As an example, a six-strut tetrahedron with its four hexagonal faces and four triangular ones is especially well-matched to hexagonal mirror segments, and multiple units can be combined to produce a large mirror support with an areal density less than 0.1 kg/m^2 using thin-walled plastic tubes. Specifically, the critical buckling load is 3.7 kgf (far greater than should be expected with use in space) and the individual element mass is 16.5 g (i.e., 99 g for six elements) for 3 cm diameter, 1 m long tubes, with a wall thickness of 125µ.. Such a configuration is shown schematically to the left in Fig.7 with mirror mount points designated by the black circles, and the photograph on the right illustrates a grouping using three individual tensegrities. This particular realization is probably less than ideal because many of the ends would have to be hinged with their neighbors, but the design does have no bending moments, and deployment from a small stored volume can be accomplishing by using the tension elements that attach at the black squares.

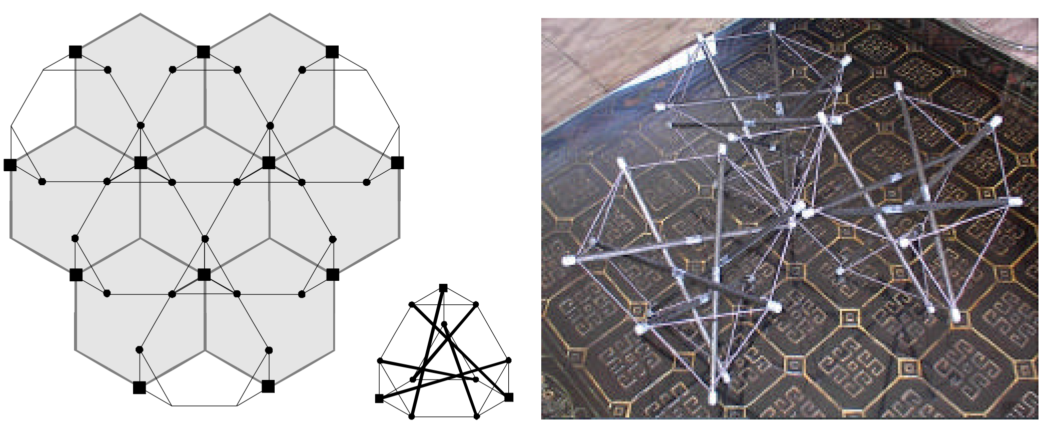

Fig. 7 Tensegrity space frame

A fundamentally-different tension-based concept is shown to scale in section view in Fig. 8 for an f/1.25 parabola. This would employ some type of inflatable torus with diametrical tension cables arranged geometrically to

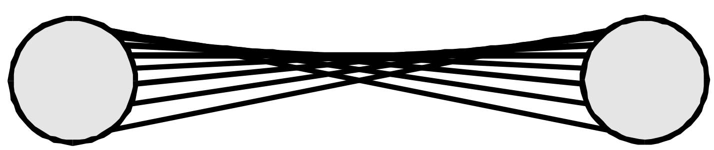

Fig. 8 Toroidal mount with tensioned mirror supports

produce the desired surface figure, and the tension in the mirror support cables could be adjusted to accommodate variations in the boundary dimensions. Such a concept is particularly attractive

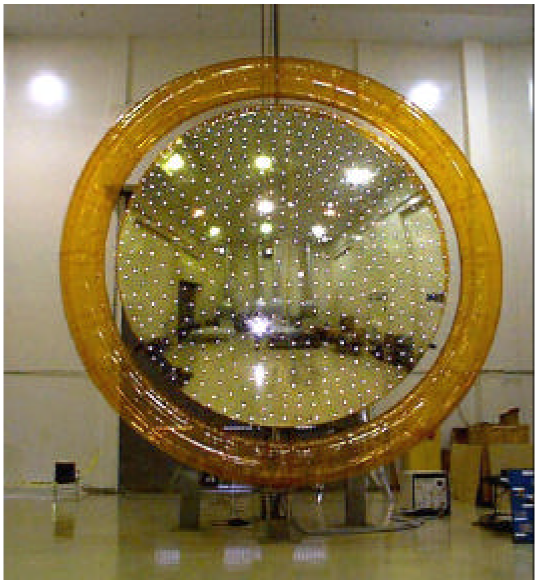

Fig. 9 SRS Technologies 5 meter antenna

because of successful efforts to develop large antennas and solar collectors for use in space, a striking example being the SRS Technologies 5-meter toroid-based antenna shown in Fig. 9. The 51 lb total weight corresponds to 1.18 kg/m^2, but it's important to note that less than 14% of that weight is due to the membrane material in the torus (4.5#) and the concentrator (3#); most of the remainder is in the three support struts (16.5#), the inflation control (10#), and the support ring (10#.) Yet another example (Fig. 10) from the non-optical world is the 78 kg, 12.25m deployable wire mesh reflector (0.66 kg/m^2) being developed by Astro Aerospace Corp. for the Thuraya cellular phone communications satellite. *These examples are particularly useful for putting into perspective the measures that must be taken and the types of technology that must be employed to achieve ultra low mass in space, and their state of development suggests that the optical community might be wise to turn to the communications world for structures rather than trying to reinvent them..*

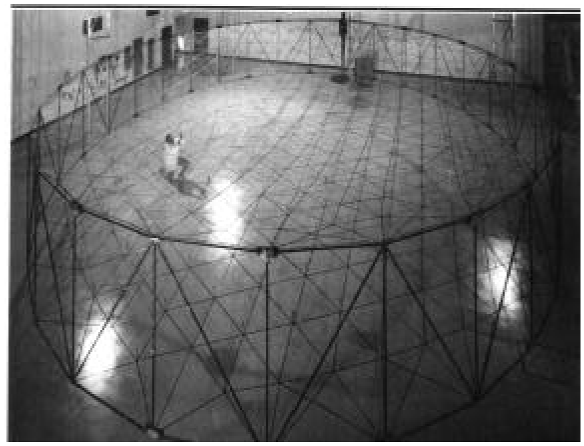

Fig. 10 Thuraya wire mesh reflector

The mirror panels must themselves be stowed and deployed without damage, but that can prove to be a very difficult matter because of their delicate surfaces. An obvious approach would be to stack and deploy them like a deck of cards, but another very interesting idea suggested several years ago by Dr. John Dimmock of UAH/CAO would use a hinge/clamp toggle mechanism to connect panels as shown in Fig. 11 for the example of a 19-element module. The elements would be stacked as shown in the upper figure and would be unfolded from the center along the dashed path at the lower left, perhaps using springs and fusible links for automatic deployment. The toggle can be designed to have enough freedom in its open position that the panels can be moved laterally into position before being locked into place. This

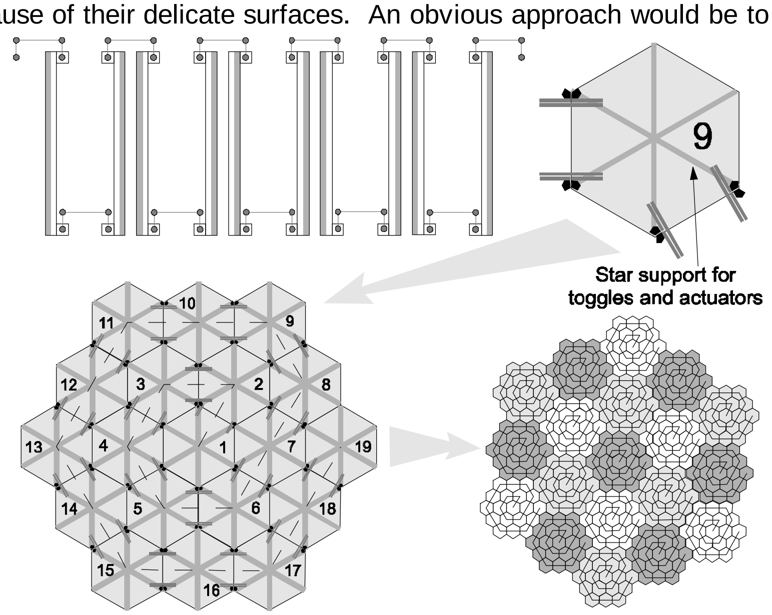

Fig. 11 Mirror panel storage and deployment concept

scheme could be used quite effectively in a 19-module array with hierarchical control to produce an array with 361 1+ meter elements to yield a 20 meter primary mirror. The clamping mechanism, when coupled with a simple star structure under each panel, would provide a base for each module, and the assembly would in turn be mounted on the truss structure.

4. Mirror Segments

Lightweight support structures will be of little value if the mirror themselves are heavy, so we have sought to apply the design principles outlined in Ref. 3, the most important of which are (1) to have a thin mirror surface that provides only *local* structural support for itself and (2) to use a dedicated "thick" backup structure to provide global support. The problems with applying this concept to metals and composites are (1) that the two sections should be made of the same material to minimize differential thermal expansion between them (or be otherwise thermally matched) and (2) that the backup structure not deform the face sheet when the two are joined, and we suggest that the answer may lie in the use of thermally-formed plastics.

Although the inherent strength of such materials is clearly inferior to that of metals and composites, they have the distinct advantage of being able to be shaped at elevated temperatures to accurately replicate a precision surface, and multiple elements can further be bonded into homogeneous designs that display minimal thermal deformation aside from simple expansion. The approach is based on the well-known fact (examples include I-beams and egg crate designs) that the deflection of a plate depends far more on the depth than it does on the internal details, so a very stiff, light structure can be made from thin plastic that is heat-formed to produce a sufficiently high moment of inertia. For example, 5 mil polyimide film (areal density = 0.175 kg/m^2) can be heated to produce a structure whose depth is about 70% of the 2-D web spacing. Such structures have been successfully fabricated using a pressurized machined mold, and a particularly attractive configuration results when a mold is cross milled to produce “posts” as shown in Fig. 12, and the post faces of two molded sheets are then bonded to produce a strong lightweight panel. Calculations suggest that an optimally three-point-supported disk with such construction should display an RMS deflection of less than 10 nm under its own weight at 1 g with a diameter of 10 cm, and the same design would experience that deflection at 10^{-4} g with a diameter of 1 meter. It should be noted that the δ/A^2 scaling is well based in theory, so test results at 1g with a given local structure can be readily extrapolated to low-g operation.

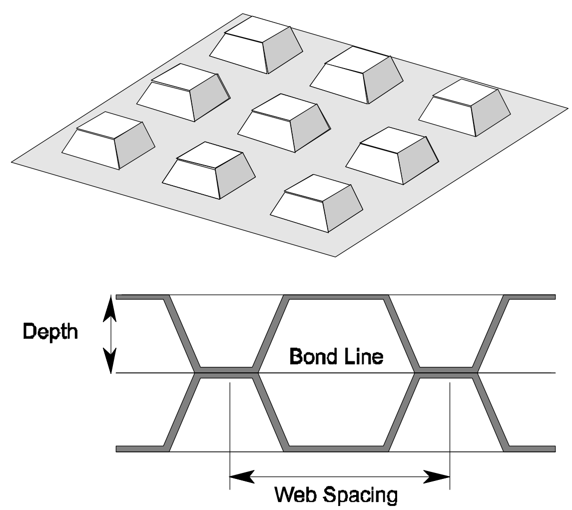

Fig. 12 Heat-formed plastic structure

It should then be possible to convert this to a mirror by appropriately bonding a face sheet of the proper figure to one of the sides. The sheet can either be pre-metallized for high reflectivity or a reflective layer can be vacuum-deposited after fabrication. The web spacing of the support structure in this case would be matched to the face sheet to yield acceptable deformation, typical dimensions for sub-micron deformation being about 1 cm web spacing for a 5 mil surface at 1 g, and 10 cm at 10^{-4} g. Such a mirror composed of three 5 mil sheets would have an areal density of 0.525 kg/m^2, but this could conceivably be reduced to as little as 0.125 kg/m^2 using 1 mil plastic instead throughout.

Fig. 13 shows a prototype that was quickly produced for use in this paper. Few precautions were taken to provide a quality mirror surface, but the bare plastic face nevertheless produces surprisingly good reflection, and the single sheet of formed structure is remarkably stiff.

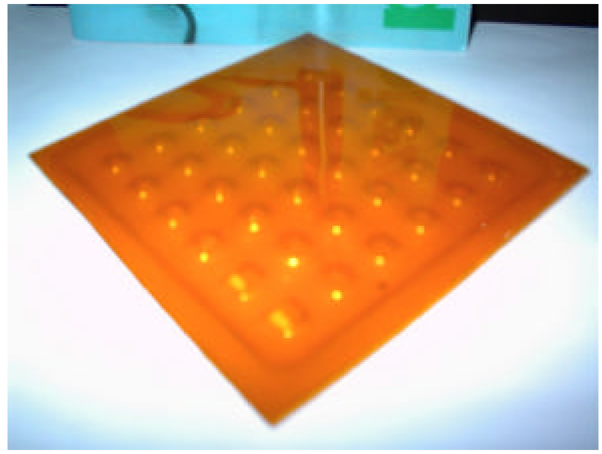

Fig. 13 Heat-formed plastic prototype

5. Conclusion

The technology to support the use of segmented optics for ultra large space telescopes continues to advance, and the concepts presented in this paper suggest they can produce primary mirror systems with an areal density of about 1 kg/m^2, effectively bridging the gap between NGST technology ($\geq$ 10 kg/m^2) and the long-term NASA goal of 0.1 kg/m^2.

6. Acknowledgement

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